LINEAR EXPANSION OF WOOD COMPOSITES: A MODEL

Wei Xu
Research Associate

and

Otto Suchsland
Professor Emeritus

Department of Forestry
Michigan State University
East Lansing, MI 48824-1222

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ABSTRACT

An analytical model was developed to better understand and predict linear expansion of wood composite panels. The model analysis was based on the assumption of elasticity and of uniform directional distribution of linear expansion. Monte Carlo simulation of the model required inputs of modulus of elasticity of solid wood, linear expansion values of solid wood, particle size distribution, and orientation distribution of particles.

The simulation showed, as expected, that lower density wood species resulted in lower linear expansion of the composite panel. In single-layer oriented strandboard, linear expansion in the orientation direction decreased gradually as percent alignment increased, but increased rapidly across the orientation direction especially when percent alignment exceeded 40–60%.

Finally, simulation results were compared with the results of experimental linear expansion studies drawn from the literature. The agreement was encouraging.

Keywords: Linear expansion, model, Monte Carlo simulation, orientation, oriented strandboard, particleboard, wood composites.

INTRODUCTION

Linear expansion (LE) is an important material property of both interior and exterior wood composite panels. For example, LE restraint can result in buckling of particleboard components (interior furniture/cabinet application); and mismatch of LE of particleboard substrate with that of overlay materials can lead to panel warping and distortion (Suchsland et al. 1995). In the case of exterior oriented strandboard (OSB), numerous instances of the so-called "window pane" phenomenon in roof applications have been attributed to the disregard of installation clearance between panels (Enlow 1996).

Despite its importance, LE remains one of the least understood properties for wood composite panel materials. It is rarely being considered in material selection or process design (Suchsland 1972). Clearly, a better understanding of the mechanism of LE is needed in order to allow its accurate prediction in various service applications and its control by process modification.

The model technique described in this paper will contribute to the understanding of LE and to the ability to predict and control LE behavior.

THE LINEAR EXPANSION MODEL

In order to facilitate model analysis of LE, the real wood composite must be replaced by a model upon which theoretical analysis can be performed. Our model development for LE analysis started from the assumption that particles are deposited perfectly parallel to the plane of the board.

Let us assume that a composite panel under this structural simplification experienced an LE, ε (%), in a specific direction as a result of a certain moisture content (MC) change. Further, let us assume that this expansion is uniformly distributed in this specific direction. This LE does not directly reflect the free expansion of individual particles, but it is rather a resultant value, depending on the fiber orientation of individual particles relative to the direction of expansion, and on the degree of expansion restraint of the bonded particles. The difference between this resultant expansion, ε, and the free expansion of individual particles in the same direction, ε_i, is $\varepsilon - \varepsilon_i = \delta_i$.

LE is the percent change in dimension that occurs as a result of MC change from one level to another, which in turn is a consequence of a relative humidity (RH) change. This expansion is a slow and gradual process. Therefore, LE can be conceptualized as the sum of a large number of "micro LE" steps. For every individual "micro" step, the MC interval and the corresponding $\delta_i = \varepsilon - \varepsilon_i$ are so small that the stresses in the particles may be assumed to be entirely elastic. We therefore disregard, for the purpose of this study, the visco-elastic characteristics of the wood material. Studies by Bryan (1962), Grossman (1973), Heebink et al. (1964), and Tang et al. (1982) on LE of wood composites were also based on the assumption of elasticity.

With this elastic assumption, the point tensile or compressive stress within a particle in the concerned direction would be $E_i*(\varepsilon - \varepsilon_i)$, and the corresponding point elastic energy (ρ_i) would be (Bodig and Jayne 1982):

$$\rho_i = 1/2*E_i*(\varepsilon - \varepsilon_i)^2 \quad (1)$$

where E_i stands for the modulus of elasticity (MOE) of wood particles in the direction of expansion.

The total energy (ϕ_i) of an individual particle in the concerned direction would be:

$$\phi_i = 1/2*\iota_i*\omega_i*\tau_i*E_i*(\varepsilon - \varepsilon_i)^2$$
$$= 1/2*V_i*E_i*(\varepsilon - \varepsilon_i)^2 \quad (2)$$

Direction of Linear Expansion

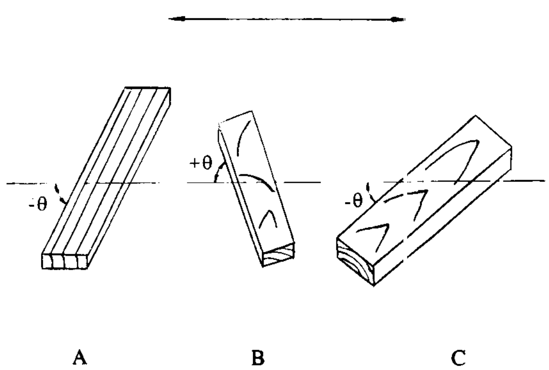

FIG. 1. A schematic showing the definition of particle configuration and orientation angle relative to the direction of linear expansion. A = longitudinal–radial (L–R) configuration; B = intermediate configuration; C = longitudinal–tangential (L–T) configuration.

in which ι_i, ω_i, τ_i, and V_i are the particle length, width, thickness, and size (volume), respectively.

The grand energy (Ø) due to LE in the whole composite system (in the concerned direction) is therefore given by:

$$Ø = 1/2\Sigma\, V_i*E_i*(\varepsilon - \varepsilon_i)^2 \quad (3)$$

The elastic assumption is also justified for predicting LE when one considers the energy concept. Since wood is a visco-elastic material and can be modeled by spring and dash-pot combinations (Lang and Loferski 1995), initially all the energy due to LE must be from elastic deformation (spring elements). As part of the elastic deformation becomes plastic or visco-elastic as LE progresses, part of the energy also changes from elastic (spring element) to plastic or visco-elastic (dash-pot element) in the spring and dash-pot combination system. However, this process of energy redistribution does not change the amount of energy. Therefore, the total energy can be calculated by the elastic assumption and is given by Eq. (3).

As each particle in the composite may be oriented at a different angle (Fig. 1), Eq. (3) can be better expressed as

$$Ø = 1/2\Sigma\ V_i{*}E_\theta(\varepsilon - \varepsilon_\theta)^2 \quad (4)$$

in which θ denotes the angle of the longitudinal direction of individual particles in relation to the concerned direction of LE (Fig. 1), and E_θ and ε_θ are, respectively, the MOE and LE of wood particles in the corresponding angular direction.

LE is a natural process without external interference; the composite system should be in the highest entropy state and possess the least amount of energy at the end of LE (when MC of composites is at equilibrium with the end RH). By taking the derivative of the grand energy (Ø) against LE (ε) in Eq. (4) and letting it equal zero, we have:

$$dØ/d\varepsilon = \Sigma\ V_i{*}E_\theta(\varepsilon - \varepsilon_\theta) = 0 \quad (5)$$

Solving Eq. (5), the LE in the concerned direction is obtained as:

$$\varepsilon = \Sigma\ V_i{*}E_\theta{*}\varepsilon_\theta/\Sigma\ V_i{*}E_\theta \quad (6)$$

This equation is similar in form to equations developed by Grossman (1973) and Heebink et al. (1964) for the LE of plywood. Their models were based on elastic assumption and equilibrium of elastic stresses and agreed well with experimental data (Heebink et al. 1964). The similarity between Eq. (6) and the models by Grossman (1973) and Heebink et al. (1964) stems from our assumption that particles in wood composites were deposited horizontally in the plane of the board and no vertical alignment was considered.

Off-axis modulus of elasticity

The calculation of ε in Eq. (6) requires the off-axis MOE as a function of the angle θ. This relationship can be expressed by the Hankinson formula (Forest Products Laboratory 1987) as:

$$E_\theta = E_1E_2/(E_1\sin^2\theta + E_2\cos^2\theta) \quad (7)$$

where E_1 and E_2 are, respectively, the longitudinal MOE and the transverse MOE.

Wood particles within a composite can assume L–T (longitudinal–tangential) configuration, L–R (longitudinal–radial) configuration, and intermediate configuration (in between L–R and L–T) (Fig. 1); an exact simulation calculation of Eq. (7) would, therefore, require the MOE in the tangential, radial, and intermediate directions. As such detailed information does not exist for all wood species, E_2 was calculated as the average of the moduli of elasticity in the tangential and radial directions where such information was available. For other species, an average of $E_1/E_2 = 16$ was used as suggested in the Wood Handbook (Forest Products Laboratory 1987).

Off-axis linear expansion

The simulation calculation of ε in Eq. (6) also requires the input of off-axis LE (ε_θ). Suchsland (1971) showed that the following equation is valid:

$$\varepsilon_\theta(\%) = \sqrt{(1 + \alpha)^2\cos^2\theta + (1 + \beta)^2\sin^2\theta} - 1 \quad (8)$$

in which α is the longitudinal LE and β is the transverse LE.

Longitudinal LE for most wood species from oven-dry to green is around 0.1%; transverse LEs (radial and tangential directions) for most wood species can be found from the Wood Handbook (Forest Products Laboratory 1987). The average of radial and tangential LEs was used as the input of β.

GENERALITY OF THE MODEL

Although Eq. (6) involves only the inputs of particle size, MOE of wood, and LE of wood, it can be shown that Eq. (6) can be applied to investigate the influence of other important processing variables. The following discussion describes such possible applications for a few selected parameters.

Adhesive type and resin content

The presence of gluelines between particles insures the stress transfer and therefore has a defining effect on the resultant expansion of the component; this was tacitly assumed in the derivation of Eq. (6). The glueline as a material component, however, has been found to be an insignificant factor with regard to LE (Suchsland 1972; Suchsland et al. 1995). The adhesive component was, therefore, ignored in the model Eqs. (6), (7), and (8). This may not be justified in cases where the adhesive component substantially exceeds present levels of 2 to 10 % (solids).

When a substantial amount of adhesives is indeed used such that material properties of particles (E_1, E_2, α, β) are modified due to resin impregnation, Eq. (6) can still be used for the analysis of LE. The influence of adhesive component can be addressed by the use of modified properties instead of solid wood properties in Eqs. (7) and (8), if the information is available.

Board density

Literature review shows that the influence of board density on LE is not conclusive. Turner (1954) and Suchsland (1972) found that LE of laboratory and commercial particleboard was not influenced by board density. Others reported either an increase or a decrease in LE as board density increased (Kelly 1977).

Even though board density was not directly involved in our model equations, it could be incorporated readily in Eqs. (7) and (8). This can be achieved by making appropriate adjustments on inputs (E_1, E_2, α, β) to account for particle densification. We are not aware of reports on the relationship between particle densification, on one hand, and LE and MOE of particles, on the other hand.

Vertical density profile

Similarly to the treatment of average board density for possible effect on LE, the vertical density profile can be incorporated in the model analysis by using a series of modified material properties as inputs in Eqs. (7) and (8) corresponding to different densification levels. There has been no report in the literature on this possible relationship between LE and vertical density profile of the board.

Thermal treatment

In the manufacturing process, wood particles are subject to thermal treatments during drying at high temperature and during the press cycle. Particles could conceivably undergo significant changes in their physical and mechanical characteristics as a result of these thermal treatments (Geimer et al. 1985; Suchsland 1972; Wolcott et al. 1994). There are indications that thickness swell decreases due to heat treatment (Halligan 1970). The possible effect of thermal treatment on LE can be addressed using the model analysis if the relationship between material properties (E_1, E_2, α, β) and thermal treatment can be established.

SIMULATION PROCEDURE

There are two approaches for the calculation of ε in Eq. (6). One approach is to experimentally prepare a plane section, measure the particle size distribution and the angular distribution of the particles in relation to the concerned direction, and count the number of particles in the plane. Another approach is to use the Monte Carlo simulation technique. The latter approach was preferred and used in this analysis. The simulation calculation proceeded as follows:

1. Obtain the angular distribution of particle orientation and the particle size distribution. For a panel of random orientation (e.g., particleboard), a uniform distribution between −90 (degrees) and 90 (degrees) was assumed for the particle orientation. For a panel made of perfectly oriented particles, θ was assumed to be zero. For a panel with imperfect orientation (OSB), the Von Mises distribution was used to describe the particle orientation (Harris and Johnson 1982).

2. Randomly pick an angle from the angular distribution and a particle size from the size distribution; calculate the off-axis MOE (Eq. (7)) and off-axis LE (Eq. (8)). The calculated values (Eqs. (7) and (8)) and the picked particle size were then used as the inputs into the appropriate terms in Eq. (6).

3. Repeat step 2 until a stable value of ε by

TABLE 1. *Modulus of elasticity and linear expansion of quaking aspen for the simulation analysis of particle size effect.*

Species	E_l (MPa)	E_l/E_2	α (%)	β (%)
Quaking aspen	8,137	16	0.1	5.37

Eq. (6) is obtained (N = 50,000 was used in this paper).

TABLE 2. *Distribution type and distribution parameter of particle size (volume) for the simulation analysis and simulation results.*

Type of distribution	Mean (mm^3)	Standard deviation (mm^3)	Linear expansion (%)
Uniform	100	0	0.26
Uniform	100	14.4	0.26
Uniform	200	57.7	0.26
Lognormal	100	14.4	0.26

MODEL SIMULATION

In the following, the model simulation is applied to the investigation of the influence of particle size, wood species, and orientation level on LE of wood composites. Two board types, a particleboard, and a single-layer OSB, were constructed from data obtained from the Wood Handbook (Forest Products Laboratory 1987).

Particle size (volume)

It appears that the majority of studies in the literature observed a reduction in LE by the use of larger particles (Kelly 1977); discrepancies to this observation also existed. For example, one recent study (Hiziroglu and Suchsland 1993) suggested that LE increased through the use of larger screen fraction particles. If particles are of uniform size (i.e., there is no variability), particle size would cancel from our model Eq. (6) and it has no influence on LE. One complicating factor associated with particle size is the tendency for preferential orientation. Preferential orientation in machine direction is well known in commercial production, especially when large particles are used. (The influence of orientation of particles in the plane of the board was examined later in this paper; the influence of vertical alignment on LE is currently being investigated and will be reported in the future.)

When particles are not of uniform size, particle size can not cancel from Eq. (6). The possible influence of particle size variation on LE was then simulated using the model analysis. The model simulation was based on a quaking aspen (*Populus tremuloides*) particleboard and an RH change from 50% to 80% (an MC content change of 6.8% was assumed). Table 1 lists the material properties (E_1, E_2, α, and β) of quaking aspen for the model analysis.

Two types of distribution (Uniform and Lognormal) and three sets of distribution parameters (mean and standard deviation) were selected to simulate the possible influence of particle size variation on LE (Table 2). The simulation results (Table 2) clearly show that LE of particleboard is independent of particle size variation. (However, particle size and its variation do influence the variability of LE measurement, which will be discussed in a separate paper.)

Since our model simulation of LE is independent of particle size and its variation, particle size (v_i) was dropped from Eq. (6) for subsequent model analysis (this is equivalent to assuming a uniform or a unit particle size).

Particleboard

Ten species were selected to simulate how material properties might influence LE of particleboard (Table 3). RHs of 50% and 80% were used as the two end conditions (a corresponding MC change of 6.8% was assumed). The use of RH change from 50% to 80% was based on the intended interior application of particleboard (National Particleboard Association 1994).

The simulation results are shown in Figs. 2 and 3. LE of particleboard increased as transverse LE of wood increased (r = linear correlation coefficient) (Fig. 2). The simulation also showed that LE of particleboard increased as longitudinal MOE of wood increased, but

TABLE 3. *Species and associated properties for the model simulation**.

Species	Density (g/cm^3)	E_l (MPa)	E_l/E_2	β (%)
Black walnut (*Juglans nigra*)	0.55	11,585	13.6	7.11
Douglas-fir (*Pseudotsuga menziesii*)	0.48	13,448	17.4	6.61
Eastern cottonwood (*Populus deltoides*)	0.40	9,448	16	7.01
Loblolly pine (*Pinus taeda*)	0.51	12,344	16	6.50
Quaking aspen (*Populus tremuloides*)	0.38	8,137	16	5.37
Red oak (*Quercus rubra*)	0.63	12,551	16	6.72
Sitka spruce (*Picea sitchensis*)	0.40	11,242	18	6.27
Sweetgum (*Liquidambar spp.*)	0.52	11,310	14.3	8.58
Yellow birch (*Betula alleghaniensis*)	0.62	13,861	16.4	9.17
Yellow-poplar (*Liriodendron tulipfera*)	0.42	10,896	17.1	6.84

* The values are from Wood Handbook (Forest Products Laboratory 1987). Density was based on oven-dry weight and volume at 12% moisture content. Modulus of elasticity was measured at 12% moisture content. E_l/E_2 was assumed to be 16 for red oak, loblolly pine, eastern cottonwood, and quaking aspen. Linear expansion was from oven-dry to fiber saturation point (30%). Longitudinal linear expansion was taken to be 0.1%; transverse linear expansion was the average of radial and tangential linear expansions.

there was a larger variation in this relationship (Fig. 3). Since longitudinal MOE and transverse LE of wood are positively correlated to wood density (Table 3), it appears that wood density was also an indicator of the linear stability of particleboard (Fig. 4), even though it was not as good an indicator as transverse LE of wood. Particleboard made from denser wood species is likely to have higher LE than particleboard made from lighter wood species, based on the simulation.

Wood particles used in the simulation were thought to be from mature wood of old forest growth; the longitudinal LE was assumed to be 0.1% for all the species involved (Forest Products Laboratory 1987). Juvenile wood, reaction wood (compression, tension and cross-grained wood), and other anatomically abnormal wood are known to have larger LE in the longitudinal direction (Lu et al. 1994; Forest Products Laboratory 1960). Subsequently, the influence of longitudinal LE of wood on LE of particleboard was also simulated. The simulation was based on a quaking aspen particleboard and the same RH change from 50% to 80%, and was performed over the range of 0% to 0.4% for longitudinal LE. The transverse LE (β) and MOE (E_1, E_2) were kept constant.

Figure 5 shows the simulation results. LE

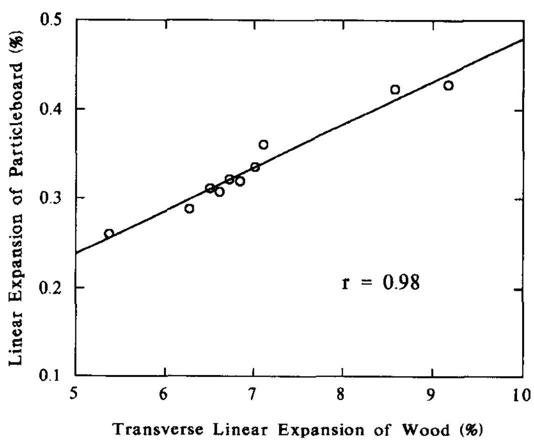

FIG. 2. Simulated linear expansion of particleboard in relation to transverse linear expansion of wood.

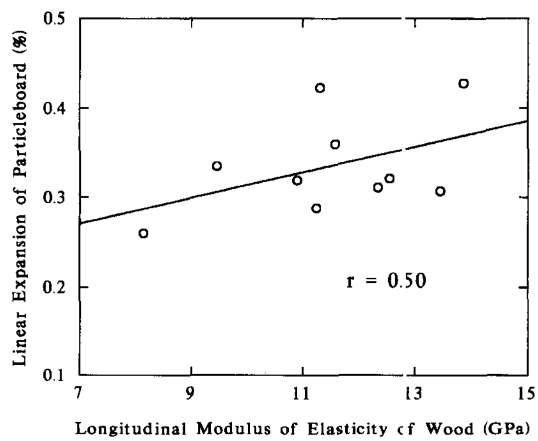

FIG. 3. Simulated linear expansion of particleboard in relation to longitudinal modulus of elasticity of wood.

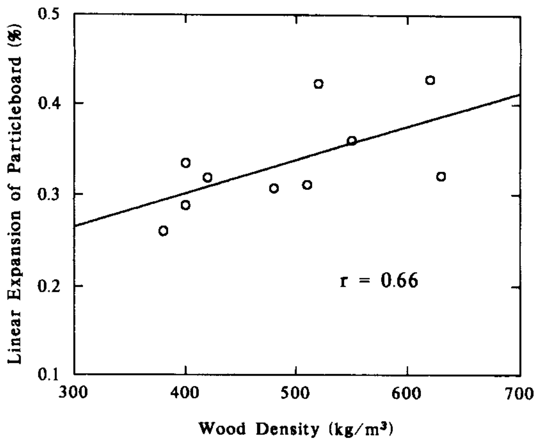

FIG. 4. Simulated linear expansion of particleboard in relation to wood density.

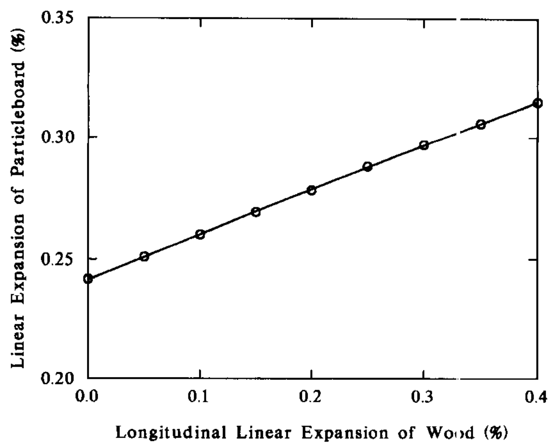

FIG. 5. Simulated linear expansion of particleboard in relation to longitudinal linear expansion of wood (wood species: quaking aspen).

of particleboard increased as the longitudinal LE of wood increased; the results agreed with the conclusions by Heebink et al. (1964) and Hiziroglu and Suchsland (1993), respectively. Especially, the perfect linear response of the simulated LE of particleboard to the longitudinal LE of wood agreed well with the finding of Heebink et al. (1964).

Recent changes in wood resources have led to increased use of juvenile wood, which might also have different transverse LE (β) and elastic properties (E_1, E_2) than normal, mature wood. A thorough evaluation of juvenile wood with regard to LE using the model simulation would require a data base of all the material properties for Eqs. (7) and (8) (E_1, E_2, α and β).

Single-layer oriented strandboard

Simulation analysis on OSB requires the input of orientation angle of particles, which can be described by the Von Mises distribution (Harris and Johnson 1982). Figure 6 shows the cumulative probability functions of the Von Mises distribution for several concentration parameters (k) (Marida 1972). In order to facilitate model simulation, these cumulative distributions were fitted by a mathematically invertible function in the form of:

$$y = a - b^* \exp(-(x + c)/d)^f \qquad (9)$$

in which a, b, c, d and f are constants to be determined by regression analysis. Table 4 lists these constants for the concentration parameters (k) used for the simulation.

The efficiency of orientation can also be measured by a more practical descriptor (Geimer 1976):

$$\text{Align\%} = 100^*(45 - \varphi)/45 \qquad (10)$$

where $\varphi = \Sigma|\text{measured angle}|/(\text{sample size})$. Shaler (1991) showed that these two measures (Align% and k) of orientation are interrelated

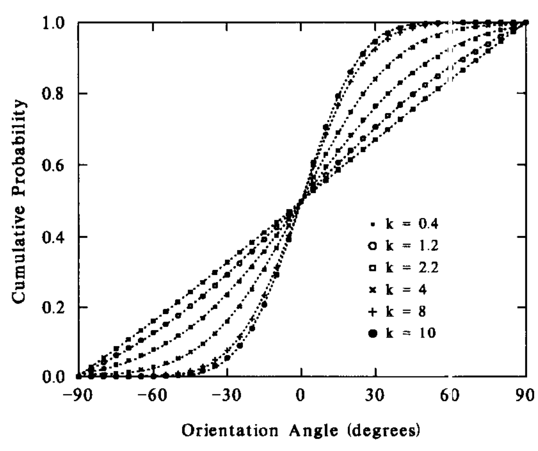

FIG. 6. Influence of concentration parameter (k) on the cumulative probability distribution of the orientation angle.

TABLE 4. *Regression constants in Eq. (10) for different concentration parameters (k)*.*

k	0.4	1.2	2.2	4	8	10
a	2.175	1.108	1.005	1.001	1.001	1.001
b	−2.646	−1.197	−1.006	−1.002	−1.002	−1.002
c	241.532	192.212	126.234	91.395	63.788	56.889
d	372.101	215.646	140.910	101.510	70.916	63.245
f	1.809	3.264	3.388	3.492	3.503	3.503

* The coefficient of determination (R^2) of the equations for all the concentration parameters (k) exceeded 0.999.

and convertible. As concentration parameter (k) increases, percent alignment (Align%) increases. Table 5 lists the correspondence of Align% for the concentration parameters (k) used in the simulation. In this study, Eq. (9) was used to provide the input of orientation angle for simulation; and percent alignment (Align%) based on Eq. (10) was used to report the simulation results as it is a more practical and conceivable orientation parameter.

Two species, quaking aspen (*Populus tremuloides*) and southern pine (*Pinus taeda*), were used to simulate how orientation might influence LE in the orientation and across the orientation directions of single layer OSB. These two species were selected because they are the major species for OSB manufacture. A more severe RH change from 30% to 90% (a corresponding 14.4% MC change was assumed) was used for the simulation to reflect the exterior application of OSB.

Figure 7 shows the simulation results for the two species in the two principal directions. As expected, southern pine single-layer OSB had larger LE in both directions than aspen single-layer OSB. While the difference of LE decreased in the orientation direction as the percent alignment increased, the difference increased across the orientation direction as the percent alignment increased. However, the influence of species on LE was minimal in comparison with the influence of particle orientation. LE in the orientation direction decreased as the percent alignment increased; the reduction of LE in the orientation direction was achieved at the expense of LE across the orientation direction.

The simulation analysis also showed that LE across the orientation direction increased at an increased rate when the percent alignment exceeded 40–60%. In a laboratory study, Geimer (1976) also showed that LE across the orientation direction increased significantly when percent alignment exceeded 40–60%. This suggests that LE in the cross-machine direction would be significantly larger if there was no sufficient restraint in the cross-machine direction of three-layer OSB. (Our future publication will discuss the contribution of the orientation in the cross-machine direction.)

TABLE 5. *Relationship between concentration parameter (k) and percent alignment (Align%)*.*

K	0.0	0.4	1.2	2.2	4	8	10	∞
Percent alignment (%)	0	15	40	60	73	82	84	100

* Data are from Shaler (1991).

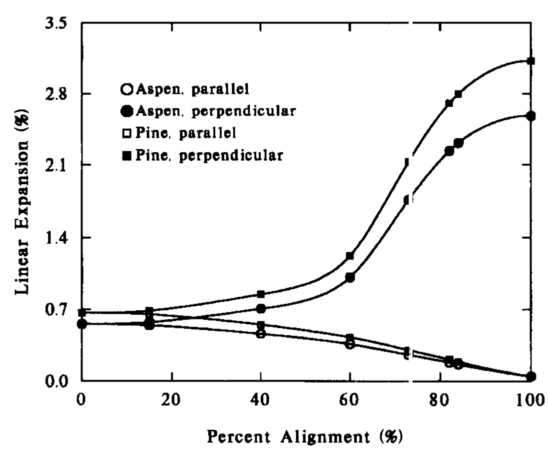

FIG. 7. Simulated linear expansion of aspen and southern pine single-layer oriented strandboard to percent alignment of particles in the orientation and across the orientation directions.

TABLE 6. *Studies and associated test conditions used for comparison with the model analysis.*

Study	Species	Relative humidity change
Coleman and Biblis (1976)	Cottonwood	30%–65%–90%
	Southern pine	30%–65%–90%
Hiziroglu and Suchsland (1993)	Quaking aspen	50%–80%
Kelly et al. (1982)	Southern pine	30%–90%
Heebink and Hann (1959)	Red oak	0%–30%–65%–80%–90%

VERIFICATION OF THE MODEL

Although there exist numerous reports in the literature on LE of wood composites, few can be used readily to compare with results of our model analysis, because of lack of data on raw materials used, exposure conditions, and MC levels reached. Table 6 lists a few selected studies from the literature and their associated exposure conditions for verification of our model. True equilibrium was assumed for the composites to estimate the MC change for model analysis.

Figure 8 shows the comparison between the measured and the predicted LEs for the selected studies. The comparison showed that the prediction agreed reasonably well with the measured values when the upper RH was less than 80% (open symbols). However, the model predictions clearly far exceeded measured values when upper RH was 90% (filled symbols). The overprediction might arise in part from the uncertainty of true equilibrium and true MC change reached in the experimental studies. We conclude from this limited comparison that the model analysis is a useful tool in LE studies; at least it is a qualitative evaluator for the practitioner.

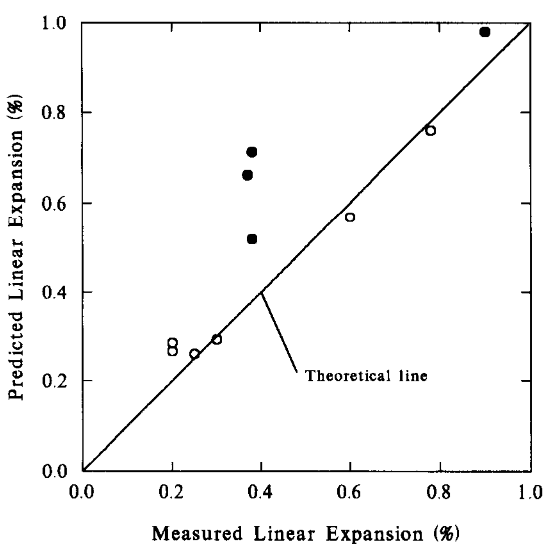

FIG. 8. Comparison of measured linear expansion and model predicted linear expansion. The measured values were read from the figures of corresponding literature and were the average if more than one board condition was involved. The filled symbols indicate that an upper relative humidity of 90% was used. The open symbols indicate that an upper relative humidity less than or equal to 80% was used.

CONCLUSIONS

The practical model developed in this paper adds to the understanding of the mechanism of linear expansion. Monte Carlo simulation clearly showed that linear expansion of wood components and orientation distribution of particles are the two important factors controlling linear expansion of wood composite panels. Other processing variables (e.g., adhesive type and resin content, board density, vertical density profile, thermal treatment, etc.) might have secondary influence on linear expansion through the modification of elastic, linear expansion, and hygroscopic properties of wood.

The practical model should be a useful tool to the practitioner in several ways. For example, particleboard manufacturers can use the model to guide the selection of proper species or species combinations for linear expansion control. Laminators can use the model to predict the linear expansion of particleboard substrate and choose compatible overlay materials to avoid warping problems. Oriented strandboard producers can use the model to determine the proper orientation level for optimum balance of mechanical properties and linear expansion.

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